PNWD-3431

A Regionally Disaggregated Global Accounting of CO_2 Storage Capacity: Data and Assumptions

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May 2004

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Printed in the United States of America

ABSTRACT

This technical working paper lays out the assumptions and data sources used to calculate a regionally disaggregated global assessment of the carbon dioxide (CO_2) storage capacity of various geologic reservoirs. We present estimates of CO_2 storage capacity in the following classes of reservoirs: depleted oil plays, coal beds, depleted gas basins, on-shore deep saline formations, and off-shore deep saline formations. CO_2 storage capacity for each of these classes of candidate geologic reservoirs were estimated by consulting the technical literature and through our own technical judgment for the following regions of the globe: USA, Canada, Western Europe, Japan, Australia and New Zealand, the Former Soviet Union, China, the Middle East, Africa, Latin America, Southeast Asia, Eastern Europe, Korea, and India. Within each of these regions and for each class of candidate CO_2 storage reservoir we have disaggregated the regional CO_2 capacity into four grades of the resource. Each grade is described by its own cost of storage. These data have been assembled so that we can employ a new version of the MiniCAM Integrated Assessment Model, known as ***ObjECTS→MiniCAM.*** It is our intent to update this dataset describing the regional distribution of candidate CO_2 geologic storage capacity as new information becomes available and also to bring this new knowledge into the evolving *ObjECTS* Integrated Assessment Model.

KEY WORDS

Geologic CO_2 storage reservoirs; integrated assessment; climate change.

Introduction

This technical working paper lays out the assumptions and data sources used to calculate a regionally disaggregated global assessment of the carbon dioxide (CO_2) storage capacity of various geologic reservoirs. We present estimates of CO_2 storage capacity in the following classes of reservoirs: depleted oil plays, coal beds, depleted gas basins, on-shore deep saline formations, and off-shore deep saline formations. CO_2 storage capacity for each of these classes of candidate geologic reservoirs were estimated by consulting the technical literature and, as needed, through our own technical judgment, for the following regions of the globe: USA, Canada, Western Europe, Japan, Australia and New Zealand, the Former Soviet Union, China, the Middle East, Africa, Latin America, Southeast Asia, Eastern Europe, Korea, and India.

These data have been assembled so that we can employ a new version of the MiniCAM Integrated Assessment Model, which is embedded in an object oriented modeling framework. This new modeling framework is known as ***ObjECTS→MiniCAM***, where ObjECTS refers to the **Obj**ect-oriented **E**nergy-**C**limate-**T**echnology **S**ystem. ***ObjECTS*** is a flexible model embodiment framework, coded in C++, capable of representing and solving alternative model equation formulations (e.g., ObjECTS can also be used to represent and solve the equation structure of the Second Generation Model as well). ObjECTS→MiniCAM version 2004.04 solves the equation structure for MiniCAM, described in Edmonds, et. al. (2004).

The MiniCAM equation structure has been enhanced to include regional representations for the cost of CO_2 storage in five alternative reservoir types: depleted oil plays, coal beds, depleted gas basins, on-shore deep saline formations, and off-shore deep saline formations. Each of these reservoir classes is, in turn, are divided into four distinct resource grades. Each grade is described by its own cost of storage and a maximum availability of potential storage capacity. The literature, and as noted in Textbox 1 a key report from the IEAGHG, at times provided information that allowed us to estimate the distribution of a specific reservoir type's aggregate sequestration capacity (e.g., depleted oil fields) within a specific region was distributed across these four grades. However for the most part, the literature simply presented an aggregate figure for a nation's capacity and therefore in these cases we were forced to use

Textbox 1: Key Assumptions for CO_2 Storage Capacity in Depleted Oil and Gas Formations

Many of our data draw heavily on (IEAGHG 2000) and in particular Appendices 1A, 1B and 1C of this report. These appendices list estimated reserves, production, EOR potential and CO_2 storage potential for the most prolific 155 basins in the world. We chose the following criteria to allocate this storage capacity across the four grades we are using to classify the CO_2 storage capacity within each region:

- Grade 1 = storage capacity in onshore oil and gas fields that are in close proximity to major CO_2 point sources
- Grade 2 = storage capacity in onshore oil and gas fields that are a medium to long distance from majorCO_2 point sources
- Grade 3 = storage capacity in <u>offshore</u> oil and gas fields that are in close proximity to major CO_2 point sources
- Grade 4 = storage capacity in <u>offshore</u> oil and gas fields that are a medium to long distance from majorCO_2 point sources.

These simple rules for allocating the capacity among the grades is based upon the authors' knowledge about the location and characteristics of the basins (see cited General References). To improve our knowledge of these reservoirs, there is clearly a need for more comprehensive, international basin- and formation-scale capacity estimates. These data will be updated as they become expert judgment to distribute this aggregate value across the grades. It will likely only be through a series of detailed national/regional assessments of candidate reservoirs that we will be able to derive significantly improved estimates of how a nation/region's geologic storage potential is graded.

Nonetheless, these grades are an important part of this analysis and an important part of better representing geologic sequestration capacity. These grades are needed so that the model can represent the real world situation of an increased supply of a good being offered in response to a willingness to pay a higher price. In the context of CO_2 storage in geologic reservoirs, these grades will allow us to represent the dynamic of entities being willing to push into distant or marginal CO_2 storage reservoirs as the demand for CO_2 storage were to outstrip the supply of inexpensive storage reservoirs.

It is our intent to update this dataset describing the regional distribution of candidate CO_2 geologic storage capacity as new information becomes available and to bring this new knowledge into the evolving *ObjECTS* Integrated Assessment Model. Table 1 represents our current regional estimates of global CO_2 storage capacity, while Figure 1 is a visual representation of the geographic distribution of storage capacity around the world.

Table 1: CO_2 Storage Capacity my Region (Gt CO_2)

	Coal Basins	Depleted Oil Plays	Gas Basins	Deep Saline Formation On-shore	Deep Saline Formation Off-shore	Total
USA	60	12	35	2,730	910	3,747
Canada	5	1	4	1,000	250	1,260
Western Europe	4	7	41	72	143	266
Japan	1	0	0	0	0	1
Australia and New Zealand	30	1	10	204	475	720
Former Soviet Un.	19	22	255	372	1,385	2,054
China	13	5	9	331	33	389
Middle East	0	32	191	223	15	461
Africa	7	14	63	116	232	433
Latin America	5	15	47	187	56	311
Southeast Asia	24	4	29	120	179	355
Eastern Europe	3	1	7	107	11	129
Korea	0	0	0	0	0	1
India	6	1	7	186	186	385
TOTAL GLOBAL CAPACITY: ALL GRADES	176	115	697	5,647	3,877	10,512

Figure 1: CO_2 Storage Capacity by Region (Gt CO_2)

The remainder of this paper will be devoted to describing the data sources and methodologies used to compute sequestration capacity within these 14 global regions and how that capacity was allocated across the four resource grades.

United States:

- Data for depleted oil, depleted gas, coal seams and deep saline formations are taken from Dooley, et. al. 2004 which was a detailed multi-year study of geologic sequestration potential in the United States and Canada.
- Distributing the overall CO_2 storage capacities across the four grades for each reservoir class was estimated by examining the more detailed cost curves that are the basis of the Dooley, et. al. 2004 study and looking for "natural" breaks in the cost curve.
- The authors have assumed that the storage capacity for offshore deep saline formations in the United States is one-third the size of the onshore deep saline formation potential. We assume that this capacity is distributed across the four grades in a way that mirrors the distribution of the capacity across the four grades for onshore deep saline formations in the United States contained in Dooley, et. al. 2004.

Canada:

- Data for Canada (with the exception of off-shore deep saline formations) are representative of the CO_2 storage capacity of candidate CO_2 storage reservoirs found predominantly in Alberta and Saskatchewan (with minor coverage in parts of British Columbia and Manitoba).. These provinces are believed to contain the majority of Canada's CO_2 storage potential.
- Data for depleted oil, depleted gas, coal seams and deep saline formations are taken from Dooley, et. al. 2004 which was a detailed multi-year study of geologic sequestration potential in the United States and Canada.
- The large capacity for deep saline formations (on shore) is largely attributable to very large capacity of the large deep saline formations contained within the Alberta Basin. The massive capacity of this formation was divided evenly among the four grades. This was simply a guess on our part.
- The large capacity for depleted gas basins comes from an assessment of a number of smaller depleted gas basins contained in Dooley et. al. 2004. While there are numerous data points along this supply curve for Canadian depleted gas basins, they all fall in a very narrow price range. This large capacity was divided evenly among the four grades. Once again, at this point, this represents a guess on our part.
- Data on coal bed storage capacity and depleted oil plays were all taken from Dooley, et. al. 2004 and were divided into the four grades by looking for natural breaks in the cost of storage in their individual supply price curves.
- Offshore deep saline formations were assumed by the authors to be ¼ the capacity of the onshore deep saline formation capacity with the majority of this capacity being in the grades 3 and 4 as relatively few large Canadian CO_2 point sources lie near the coastal areas. The assumed distribution across the four grades is as follows: grade 1 (10%), grade 2 (10%), grades 3 and 4 (40% each).

Western Europe:

- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology described in Textbox 1.
- The IEAGHG (1998) estimates that there is potentially 1.9 Gt CO_2 storage capacity in the Saar coal basin in France and Germany. The authors believe that this is likely a significant understatement of the true CO_2 storage potential of coals in Western Europe and therefore we are assuming that twice this reported capacity is available. As a first approximation, we have used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4. The one modification we made to this methodology was to move 10% of the total capacity into Grade 1 as the IEA report did not identify any coals as being in the "CBM

Resource Type A" category and we believe that there are likely some low cost coal opportunities within Western Europe.

- We estimate that the storage capacity of onshore deep saline formations is equal to 1.5 times the capacity of all depleted oil and gas fields. We assume that grades 1 and 2 each contain 25% of the storage potential, grade 3 contains 40% of the capacity and grade 4 contains 10% of the total storage potential.
- Offshore deep saline formations were assumed to have twice the storage capacity of Western European onshore deep saline formations. The distribution of this capacity is heavily skewed towards grades three and four which reflects an assumption on our part that there will be significant infrastructure costs associated with accessing deep saline formations in, for example, the North Sea, but once these costs are paid there is a very large storage capacity read to be exploited. We assume that grades 1 and 2 each contain 5% of the storage potential, while grades 3 and 4 each contain 45% of the capacity.

Japan:

- Akimoto et. al. (2003) identify 378.5 MtC of storage capacity in offshore deep saline formations capacity. Akimoto asserts that their assumptions for capacity in offshore fields is conservative and that they only assessed regions with known anticline structures and with high quality data. The distribution of these offshore deep saline formations across the grades is based upon our reading of Figure 8 in Akimoto et.al.'s paper and the implied proximity of major CO_2 point sources to these offshore deep saline formations.
- We assume that useable on-shore deep saline reservoirs are 1/10 the size of offshore reservoirs and are distributed among the grades in the same way that the offshore deep saline reservoir are.
- We assume that useable depleted gas fields are the same capacity as on-shore deep saline reservoirs and are distributed among the grades in the same way that the offshore deep saline reservoir are.
- Komaki (2004) states that the CO_2 storage capacity of coals in Japan is "10 billon tons." The authors believe that this is likely a significant overstatement of the storage capacity of Japanese coals as it is significantly larger than the reported totals for regions known to have much large coal resource bases such as Canada and Western Europe. Therefore, we will use only 10% of the capacity identified by Komaki. Given that most of the coal is in Hokkaido which is far from the population and industrial centers of Honshu, we will assume that grades 1 and 2 each contain 5% of the storage potential, grade 3 contains, 10% and grade 4 contains 80% of the storage potential.
- We assume that there are for all practical purposes no depleted oil reservoirs in Japan that are suitable for storing CO_2 on a commercial basis.

Australia and New Zealand:

- Bradshaw et al. (2003) identifies 720 $GtCO_2$ as the total theoretical storage capacity for Australia.

- IEAGHG (1998) identifies 29.9GtCO_2 storage capacity contained within the Bowen (11.2 GtCO2), Sydney (7.8 GtCO2), Clarnce/Moreton (3.4 GtCO2), Gunnedah (3.2 GtCO2), and Gailee (4.3 GtCO2) coal basins. We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1. This amounted to 960 MtCO_2 in depleted oil fields and 10,100 MtCO_2 in depleted gas fields.
- This leaves 679 GtCO_2 of the original Bradshaw estimate of the nation's storage capacity unallocated. We assume that 70% of this capacity is contained in offshore deep saline formations and the remaining 30% is in onshore deep saline formations. We assume this is evenly divided among the various grades for each reservoir class.
- Given the large uncertainties in the above estimates we will simply assume that New Zealand's CO_2 storage capacity is contained within these estimates for Australia.

Former Soviet Union:

- The IEAGHG (1998) identifies an estimated 18.9 GtCO_2 of CO_2 storage capacity in the Kunetsk coal basin (13.6 GtCO2) and the Donetsk coal basin (5.3 GtCO2). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- For onshore deep saline reservoirs, we assume that their storage capacity is equal to the five times the sum of the capacity of the depleted oil and gas fields for each corresponding grade.
- We were unable to find published information on the storage capacity of offshore deep saline formations for the Former Soviet Union and therefore we simply estimated these amounts. Estimated amounts correspond to the capacity for the Caspian (grades 1&2) and Sakhalin, Baikal, and the Arctic Ocean deep saline formations (grades 3&4). The storage volume is equal to five times the onshore oil & gas capacity for each corresponding grade. We believe this to be a conservative estimate

China:

- The IEAGHG (1998) identified an estimated 12.7 GtCO_2 of CO_2 storage capacity in China contained within the Ordos coal basin (8.4 GtCO2) and various other coal basins in China (4.3 GtCO2). We used the “CBM Resource Type” classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: “CBM Resource Type A” = grade 1, “CBM Resource Type B” = grade 2, and “CBM Resource Type C” = was evenly divided among grades 3 and 4.

- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- The total capacity of onshore deep saline formations is assumed to be 25 times the total capacity of all of the identified depleted oil and gas fields. This capacity was divided among the four grades as follows: grades 1 and 2 each hold 25% of the capacity, grade 3 holds 40% of the capacity and the remaining 10% is in grade 4.
- For offshore deep saline reservoirs, we assume that their storage capacity is equal to five times the sum of the capacity of the depleted oil and gas fields for each corresponding grade (and therefore 20% of the onshore capacity of each grade).

Middle East:

- We believe that there is relatively little effective CO_2 storage capacity in coal seams in the Middle East. However, coal basins in Iran (EIA, 2001; WEC, 2001) and subsurface coal identified in Kuwait suggest that there is some coal-based storage capacity. We will assume that there is 0.3 $GtCO_2$ of coal storage capacity in the Middle East. We will divide this up as follows. This capacity was divided among the four grades as follows: grades 1 holds 20% of the total capacity, grade 2 each holds 35% of the capacity, grade 3 holds 20% of the capacity and the remaining 25% is in grade 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology described in Textbox 1.
- For onshore deep saline reservoirs, we assume that their storage capacity is equal to the sum of the total capacity of the depleted oil and gas fields. The distribution of this onshore deep saline formation storage capacity is weighted towards grades 1 (20% of the total) and 2 (40%) because of the exceptional reservoir quality and low drilling costs likely to be encountered in the Middle East. Grade 3 is assumed to contain 30% of the capacity while grade 4 contains the remaining 10%.
- Offshore acreage in the Middle East is roughly 12% of the onshore acreage. The offshore has received considerably less characterization as a whole than the onshore, so there is reasonable potential for increases in all grades. However, due to downstream fining away from the Arabian craton, we have assumed a very conservative estimate of 6% of the onshore deep saline aquifer volume. This capacity is divided up among the grades as follows: 30% in Grade 1, 30% in Grade 2, 20% in Grade 3, and 20% in Grade 4

Africa:

- The IEAGHG (1998) identified an estimated 6.8 $GtCO_2$ of CO_2 storage capacity contained within the Karoo (1.7 GtCO2) and Zambez coal basins (5.1 GtCO2) in South Africa and Zimbabwe. We used the “CBM Resource Type” classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4. This likley represents an underestimation, as it does not, at this time, account for recognized coal seams in Ethiopia, Eritrea, Chad, Niger, and Mauritania.

- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology described in Textbox 1.
- Africa's onshore deep saline formations capacity is assumed to be 1.5 times the combined total storage capacity of depleted oil and gas fields. We assume grades 1 and 2 each hold 25% of the capacity, grade 3 holds 40% of the capacity and the remaining 10% is in grades 4.
- The authors have estimated offshore deep saline formation CO_2 storage capacity based upon the values for on-shore storage capacity as follows:
    - the storage capacity for grade 1 and grade 2 offshore DSF capacity is 1.5 times that of the corresponding onshore DSF capacity,
    - the storage capacity for grade 3 is equal to twice the storage capacity of the corresponding grade 3 onshore storage capacity plus ½ the storage capacity of onshore DSF contained in grade 1,
    - the storage capacity for grade 4 is equal to twice the storage capacity of the corresponding grade 4 onshore storage capacity plus ½ the storage capacity of onshore DSF contained in grade 2.
- The capacity of these offshore deep saline formations is weighted heavily towards grades 3 and 4 due to a lack of infrastructure and very high drilling costs. Since most of Africa's basins and reserves lie offshore (e.g., Niger delta shelf and slope, Gabon and Angolan basins), even a conservative rendering produces high potential storage volumes.

Latin America:

- We were unable to find any information in the literature on the CO_2 storage capacity of coals in Mexico, Central and South America. However, the region contains many large volume coal basins, especially in Brazil and Columbia (WEC 2001). Since Latin American reserves are approximately 8% of US reserves, we have used that percentage as a crude scaling agent and assigned 5000 million tons capacity to be conservative. Most of this is apportioned to grades 1 and 2 (1500 and 2000 million tons respectively) given the relative proximity of these basins to infrastructure and population. The remainder of the capacity is divided evenly among Grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology described in Textbox 1.
- The total capacity of Latin American onshore deep saline formations is assumed to be three times the combined total capacity of the depleted oil and gas reservoirs in this region. This capacity is divided up among the grades as follows: 25% in Grade 1, 25% in Grade 2, 35% in Grade 3, and 15% in Grade 4.

- For each grade, offshore deep saline formations were assumed to contain 30% of the capacity of the onshore deep saline formation capacity in the corresponding grade.

Southeast Asia:

- The IEAGHG (1998) identified an estimated 23.9 $GtCO_2$ of CO_2 storage capacity in Indonesian coals contained within the Sumatra coal basin (13 GtCO2) and various other basins (10.9 GtCO2). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- Onshore deep saline formations were assumed to be 5 times as large as the coal basin CO_2 storage capacity. This scaling factor was used for all grades.
- Offshore deep saline formations were assumed to be 1.5 times as large as the onshore deep saline formations' CO_2 storage capacity. This is likely an understatement of the true size of these reservoirs. This 1.5 times scaling factor was used for all grades.

Eastern Europe:

- The IEAGHG (1998) estimates that 1.6 $GtCO_2$ of storage capacity exists in the coal seams of Poland and the Czech Republic, specifically with in the Upper Silesian coal basin. We believe that this might be an overly conservative estimate of CO_2 storage capacity and therefore we have doubled the capacity identified in this IEAGHG report. We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology described in Textbox 1.
- On-shore deep saline formations in Eastern Europe are assumed to be 1.5 times as large as the capacity of onshore deep saline reservoirs in Western Europe.
- Off-shore deep saline formations in Eastern Europe are assumed to be only 10% the capacity of the onshore deep saline formations in Eastern Europe.

Korea:

- We believe that there is a relatively small CO_2 storage capacity potential within South Korean coal seams. Based on the US DOE EIA estimates of global coal reserves we estimate that Korean CO_2 storage capacity in coal seams is equal to

1% of the storage capacity of coals in China and that this is distributed across the four grades in a similar manner.

- We believe that there is effectively no CO_2 storage capacity in South Korean depleted oil and gas fields, and on-shore deep saline formations.
- The authors have included a total of 0.4GtCO_2 storage capacity in offshore deep saline aquifers for Korea. This is split evenly between Grades 3 and 4 given the adjacent western basins. This is roughly 1% of China's saline aquifer storage, and Korea has about 1% of China's coal volume so it seems reasonable. Given Korea's very limited storage potential, even this small amount of relatively expensive storage might prove to be important.

India:

- The IEAGHG (1998) identified an estimated 5.5 GtCO_2 of CO_2 storage capacity in India contained within the Cambay coal basin (3.8 GtCO2) and the Damodan coal basins (1.7 GtCO2). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology described in Textbox 1.
- The authors have assumed that the storage capacity of onshore deep saline formations in India is 25 times the capacity of the total for all grades for depleted oil and depleted gas fields. We assume that the majority of this capacity will be in the higher grades and as a result have allocated this total capacity as follows: 10% in Grade 1, 10% in Grade 2, 40% in Grade 3, and 40% in Grade 4
- The authors have assumed that the storage capacity of offshore deep saline formations in India (e.g., Bengal Fan & Indus Cone) is a function of the on shore deep saline formation capacity as follows:
    - the capacity of Grade 1 off-shore deep saline formations is equal to 75% of the onshore deep saline formation capacity for that grade,
    - the capacity of Grade 2 off-shore deep saline formations is equal to 75% of the onshore deep saline formation capacity for that grade,
    - the capacity of Grade 3 off-shore deep saline formations is equal to the sum of 100% of the Grade 3 onshore deep saline formation capacity plus 25% of the capacity of Grade 1 onshore deep saline formations, and
    - the capacity of Grade 4 off-shore deep saline formations is equal to the sum of 100% of the Grade 4 onshore deep saline formation capacity plus 25% of the capacity of Grade 2 onshore deep saline formations,

  It should be said that these two sediment accumulations contain over 13 km of strata that have received very little direct or indirect study to date.

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